Elements of Modern Optical Design

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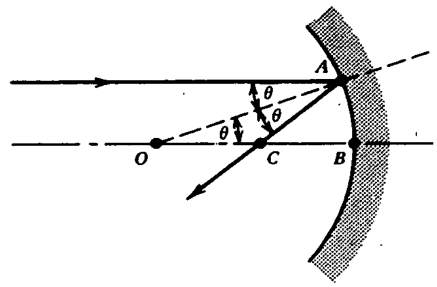

Figure 1.11. Geometry for the derivation of focal length for a concave spherical mirror.

mirrors the focal length is positive; for convex mirrors it is negative, as can be demonstrated by ray sketching with parallel incident rays.

As we examine parallel rays further from the optic axis, we find that after reflection they cross the axis at a point closer to the vertex of the mirror than the focus for small angles. This variation in the focal point with incoming ray height is a defect of a spherical mirror and is called *spherical aberration*. For the case of incident parallel rays it can be corrected by changing the shape of the mirror from a sphere to a parabola. The prescriptions for other object distances are different. Later on, we shall consider such aberrations; for the present, we assume that all our rays are paraxial rays, which exhibit no aberrations.

Before proceeding, a set of sign conventions should be set down for the thin lens calculations to be considered next and for the paraxial (Chapter 5) calculations to be done later. We use a standard right-handed coordinate system with light propagating generally along the z axis.

1. Light initially travels from left to right in a positive direction. (Refractive indices are positive in this case.)
2. Distances to the right of a component (or surface) are positive; to the left, negative.
3. Heights above the axis are positive; below the axis, negative.
4. The radius of curvature of a surface is positive if its center of curvature lies to the right of its vertex; to the left, negative.
5. Focal lengths of converging elements are positive; diverging elements have negative focal lengths.
6. Light traveling in a *negative* direction (i.e., in the z-direction), is traced in exactly the same manner except that (a) distances are reversed in sign (left, positive; right, negative) and (b) the signs of refractive indices are negative.

The change in the sign of distances holds both for inserting a value in an equation and for determining the image distance after calculation.

Having settled on the sign convention for tracing rays, it will be obvious after a re-examination of the derivation of the focal length of a spherical

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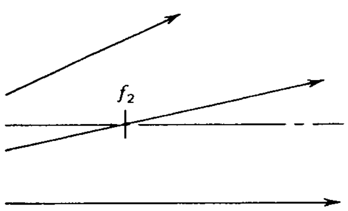

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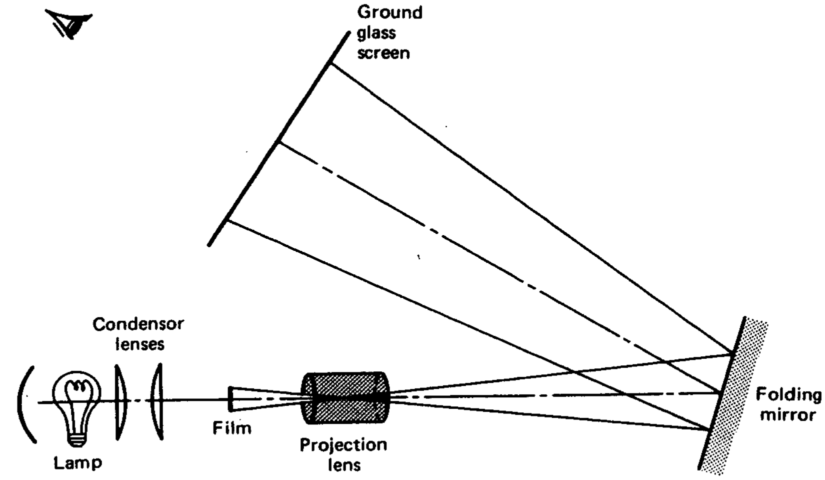

Figure 1.10. Folding a projection system to produce a more compact design and convenient screen orientation.

1.4. MIRRORS AND LENSES—CALCULATIONS

Thus far we have not put any numbers with the examples we have shown. While there are precise graphical methods for assessing an optical system, ray sketching is only used as a design shorthand. It is through calculation that we can determine if the system will do what we want it to. And it is only through these calculations that we can specify the necessary components, modify the initial values, and understand the limitations of the design. After settling on a sign convention for ray tracing, we shall derive some simple equations for mirrors and thin lenses.

Rays traced close to the optic axis of a system, those that have a small angle with respect to the axis, are most easily calculated because some simple approximations can be made in this region. This approximation is called the *paraxial approximation*, and the rays are called *paraxial rays*. This approximation can be used to derive the focal length of a spherical mirror.

A parallel ray close to the optic axis strikes the mirror at a point A, as shown in Fig. 1.11, at an angle θ to the normal to the mirror. The ray is reflected from the surface at angle θ and crosses the optic axis at the focal point C. The normal at the point A is a radius of the mirror centered at point O on the optic axis. Thus $\overline{OA}$ is equal to the radius R of the mirror. Because the incident ray and the axis are parallel, the angle AOC is also equal to θ, thus triangle AOC is an isosceles triangle and $\overline{AC} = \overline{OC}$. As the angle θ gets smaller, $\overline{AC} = \overline{BC} = f$, the focal length and $\overline{BO} = \overline{AC} + \overline{OC} = 2\overline{AC} = 2f$. But $\overline{BO} = R$; therefore $f = R/2$, for rays close to the axis. For concave